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Zeolite-Supported Tetramethyl-1,2-Dioxetane: New Pathways
to Chemiluminescence

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Prepared for Publication in

Tetrahedron

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July 8, 1987

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AD-A183123

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION NA	1b. RESTRICTIVE MARKINGS NA
2a. SECURITY CLASSIFICATION AUTHORITY NA	3. DISTRIBUTION/AVAILABILITY OF REPORT Distribution Unlimited; Approved for Public Release
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE NA	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) UWIS/DC/TR-87/2	5. MONITORING ORGANIZATION REPORT NUMBER(S) NA

6a. NAME OF PERFORMING ORGANIZATION Chemistry Department University of Wisconsin-Madison	6b. OFFICE SYMBOL (If applicable) NA	7a. NAME OF MONITORING ORGANIZATION ONR
6c. ADDRESS (City, State, and ZIP Code) 1101 University Avenue Madison, WI 53706		7b. ADDRESS (City, State, and ZIP Code) 800 N. Quincy Street Arlington, VA 22217

8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable) NA	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Contract N00014-85-K-0631

| 8c. ADDRESS (City, State, and ZIP Code) | 10. SOURCE OF FUNDING NUMBERS |

	PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO. R&T Code 4134003	WORK UNIT ACCESSION NO

11. TITLE (Include Security Classification)
Zeolite-Supported Tetramethyl-1,2-Dioxetane: New Pathways to Chemiluminescence

12. PERSONAL AUTHOR(S)
Bryan L. Benedict and Arthur B. Ellis

13a. TYPE OF REPORT Technical	13b. TIME COVERED FROM _____ TO _____	14. DATE OF REPORT (Year, Month, Day) 2/26/87	15. PAGE COUNT 9

16. SUPPLEMENTARY NOTATION
Prepared for publication in Tetrahedron

17.	COSATI CODES		18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Zeolites; dioxetanes; chemiluminescence

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The thermal decomposition of tetramethyl-1,2-dioxetane (TMD) sorbed into zeolite Y containing Eu^{3+} ions and 2,2'-bipyridine (samples abbreviated as ZYEBT) has been investigated. Decomposition of TMD yields, by energy transfer processes, chemiluminescence (CL) characteristic of the Eu^{3+} ion. At loading levels corresponding to an upper-limit average of 0.5, 1.0, and 2.0 TMD molecules per unit cell, the CL decay curves are nonexponential at short times; at longer times, roughly exponential curves are characterized by a unimolecular rate constant k. Analyses of the long-time decays based on an Arrhenius expression for the rate constant provide evidence for a kinetic compensation effect: plots of log k vs. the activation energy E_a as a function of TMD loading level are linear. Solution data (benzene, benzonitrile) fall on the same line, suggesting that TMD decomposes by a common rate-limiting mechanism in these various environments. The Arrhenius parameters (E_a and the pre-exponential factor A) are smaller than the solution values and increase with TMD loading. When
(continued on reverse side)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Distribution Unlimited
22a. NAME OF RESPONSIBLE INDIVIDUAL Arthur B. Ellis	22b. TELEPHONE (Include Area Code) 608-262-0421 22c. OFFICE SYMBOL

Approximately 7

TMD is sorbed to the extent of an upper-limit average of ~7 molecules per unit cell, CL decay curves are initially nearly flat and then show an increase in decomposition rate with time. Mechanistic implications of these results are discussed.

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ZEOLITE-SUPPORTED TETRAMETHYL-1,2-DIOXETANE: NEW PATHWAYS
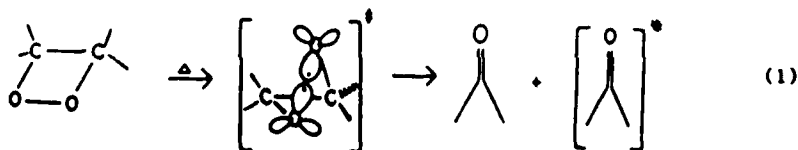## TO CHEMILUMINESCENCE

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Abstract - The thermal decomposition of tetramethyl-1,2-dioxetane (TMD) sorbed into zeolite Y containing Eu^{3+} ions and 2,2'-bipyridine (samples abbreviated as ZYEBT) has been investigated. Decomposition of TMD yields, by energy transfer processes, chemiluminescence (CL) characteristic of the Eu^{3+} ion. At loading levels corresponding to an upper-limit average of 0.5, 1.0, and 2.0 TMD molecules per unit cell, the CL decay curves are nonexponential at short times; at longer times, roughly exponential curves are characterized by a unimolecular rate constant k. Analyses of the long-time decays based on an Arrhenius expression for the rate constant provide evidence for a kinetic compensation effect: plots of log k vs. the activation energy E_a as a function of TMD loading level are linear. Solution data (benzene, benzonitrile) fall on the same line, suggesting that TMD decomposes by a common rate-limiting mechanism in these various environments. The Arrhenius parameters (E_a and the pre-exponential factor A) are smaller than the solution values and increase with TMD loading. When TMD is sorbed to the extent of an upper-limit average of ~7 molecules per unit cell, CL decay curves are initially nearly flat and then show an increase in decomposition rate with time. Mechanistic implications of these results are discussed.

In recent studies we have examined the effects of adsorption onto silica gel and intercalation into a layered solid, hydrogen uranyl phosphate (HUP), on the excited-state processes of organic and inorganic compounds. In the former case, the photoisomerization of retinal isomers,[1] the loss of CO from (η^6-arene)tricarbonylchromium(0) complexes,[2] and the luminescence and photodimerization of a dibenzylideneacetone derivative[3] are all perturbed by adsorption. Intercalation of guest species such as $Cr(NH_3)_6^{3+}$ and Eu^{3+} into HUP has provided evidence of efficient host-to-guest, excited-state energy transfer processes.[4,5]

In considering compounds whose excited-state properties might be sensitive to their environment, our attention was drawn to tetramethyl-1,2-dioxetane (TMD). As shown in eq. (1), TMD thermally

decomposes to yield an excited acetone molecule; chemiluminescence (CL) has been observed from this species (acetone fluorescence and phosphorescence)[6] and from suitable acceptor species such as Eu^{3+} complexes.[7,8] The reaction is sterically demanding. A calculated transition state is

characterized by a twisting of the peroxy ring.[9] The steric demands of the decomposition have prompted us to introduce TMD into zeolites where the host cage structure can impose its own steric constraints on the decomposition.

In this paper, we report that TMD can be sorbed in varying quantities into zeolite Y containing Eu^{3+} ions and 2,2'-bipyridine. Thermal decomposition of TMD in this host (abbreviated ZYEBT) produces, by energy-transfer processes, CL characteristic of the Eu^{3+} ions. Kinetic analysis of CL decay curves indicates that TMD occupies sites of varying reactivity in the solid. An Arrhenius treatment of the exponential portion of CL decay curves, characterized by a unimolecular rate constant k, is consistent with a kinetic compensation effect: plots of log k vs. the activation energy E_a are linear for various TMD loading levels. Moreover, solution data are fit by the same line, suggesting a common rate-limiting mechanism in these diverse environments. Evidence for a cooperative decomposition mechanism is seen at the highest TMD loading level examined.

RESULTS AND DISCUSSION

In sections below we describe the preparation and characterization of zeolite-supported TMD, its chemiluminescent properties, and the mechanistic implications of these properties.

Preparation and Characterization of Zeolite-Supported TMD. The host solid for our studies, zeolite Y, was calcined at 500°C prior to use. As sketched in Figure 1, an average unit cell of this zeolite, $Na_{57}[(AlO_2)_{57}(SiO_2)_{135}] \cdot xH_2O$, has a pore diameter of 7.4 Å and a cavity diameter of 13 Å. Initial experiments, wherein TMD was sorbed into the zeolite from benzene solution, yielded CL signals that were too weak for kinetic analysis.
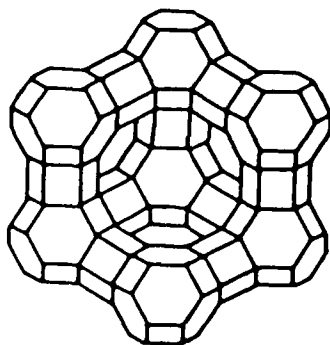

Fig. 1. Sketch of a portion of the unit cell of zeolite Y (faujasite structure). Vertices are Si or Al atoms that are tetrahedrally coordinated by O atoms.

Since Eu^{3+} complexes are known acceptors for dioxetane CL,[7,8] the lanthanide ion was exchanged into the zeolite from aqueous solution to the extent of about one ion per unit cell. After drying (200°C at 4×10^{-5} torr for 24 h), the zeolite exhibited weak pink photoluminescence (PL) characteristic of Eu^{3+} when irradiated with near-UV light. Sorption of TMD from CH_2Cl_2 solution into the exchanged zeolite yielded pink CL on warming, but of insufficient intensity for kinetic analysis. The weak PL and CL signals may be due to the presence of water molecules in the metal ion's coordination sphere, since O-H stretching modes are known to serve as efficient nonradiative decay routes.[10,11] Alternatively, the weak CL intensity may result from the presence of transition metal impurities. These species could catalyze the decomposition of TMD in the zeolite, as they do in solution.[12]

In an effort to improve the radiative efficiency of the Eu-exchanged zeolite, the solid was exposed to an ethanolic solution of 2,2'-bipyridine with the expectation that the sorbed species would chelate to Eu^{3+}, displacing water molecules. Indeed, sorption causes the radiative efficiency to increase substantially and results in a sample PL lifetime of ~1.2 msec. From correlations previously reported for Eu-exchanged zeolites, this lifetime corresponds to

essentially complete loss of water from the Eu coordination sphere.[13] Heating this sample under vacuum (10^{-4} torr at 150°C for 12 h) does not affect the PL lifetime but does remove excess bipyridine that could block channels into the zeolite system, obstructing TMD sorption. Spectrophotometric analysis of these samples after dissolution in HF indicated the presence of ~2.6-2.8 bipyridine molecules per unit cell and hence per Eu^{3+} ion. From this stoichiometry we suspect that, on average, the Eu^{3+} ions are coordinated to two bipyridine ligands with the balance of the coordination sites occupied by lattice oxygen atoms. Consistent with such a bonding scheme is the observation that a nitrate salt of Eu containing two bipyridine ligands in the coordination sphere, $Eu(bpy)_2(NO_3)_3$,[14] yields an identical lifetime within experimental error. A noteworthy feature of chelation is that it helps prevent migration of Eu^{3+} ions out of the zeolite cages on steric grounds. Moreover, chelation can serve to diminish the role of impurity metals present in the zeolite that could otherwise catalyze the decomposition of TMD.[12]

Once dried, the Eu-exchanged zeolite containing bipyridine was slurried with chilled CH_2Cl_2 solutions of TMD. The concentrations of TMD were such that complete uptake would correspond to sorption of 0.5, 1.0, and 2.0 TMD molecules per unit cell on average. Although TMD uptake appeared to be essentially complete (based on negligible quantities of acetone in the filtrate, assayed by infrared spectroscopy following refluxing of the filtrate with $CuBr_2$ as a decomposition catalyst), these concentrations should be regarded as upper limits, since some decomposition may accompany sorption. Incomplete sorption from a more concentrated TMD solution resulted in samples with an upper-limit average of ~7 TMD molecules per unit cell. It is worth emphasizing that we do not know where the TMD molecules reside within the zeolite cages, nor can we exclude the possibility that some of the molecules are present on the external surfaces of the zeolite.

<u>Chemiluminescent Properties.</u> Samples of zeolite Y containing Eu^{3+}, bipyridine, and TMD (denoted as ZYEBT) exhibit intense pink CL when heated above ~65°C. The emission is readily seen by the dark-adapted eye. At lower temperatures the CL intensity declines sufficiently slowly that a steady-state CL spectrum can be obtained. Figure 2 reveals that the spectral distribution consists of the sharp f-f transitions characteristic of Eu^{3+}. Moreover, the spectrum is blank at wavelengths below 550 nm where acetone fluorescence and phosphorescence would normally be observed, consistent with energy transfer to Eu^{3+} in ZYEBT.
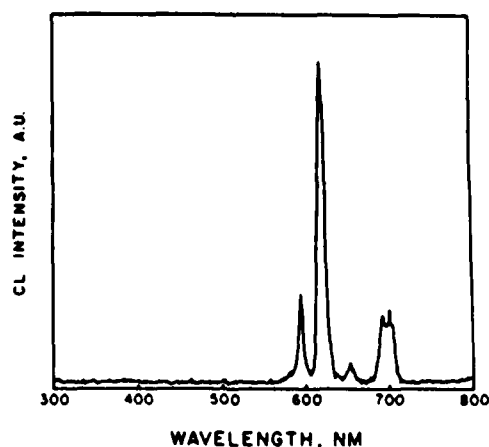

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Fig. 2. Chemiluminescence spectrum of a sample of ZYEBT (upper-limit average loading of 1.8 TMD molecules per unit cell; average of ~2.6 bipyridine molecules per unit cell) obtained at 53°C. The spectrum is a composite of two scans from 300-500 and 500-800 nm.

The intensity of the CL is presumed proportional to TMD concentration, as is found in solution studies,[15] and provides a probe of the kinetics of TMD decomposition in ZYEBT. Plots of CL intensity as a function of time generally show a slight increase at short times, presumably

reflecting the approach to the thermostatically-controlled decomposition temperature, followed by a monotonic decline. Figure 3 shows a plot of ln (CL intensity) vs. time for one ZYEBT sample at 64°C. As shown in the figure, there is often some curvature present in the early-time portion of the plots, indicating that the rate of TMD decomposition is greatest in this temporal regime; the curvature becomes less apparent with increasing temperature. As will be discussed in more detail below, the curvature is consistent with the presence of different environments (within the cages and/or on the external surfaces) for TMD in ZYEBT.
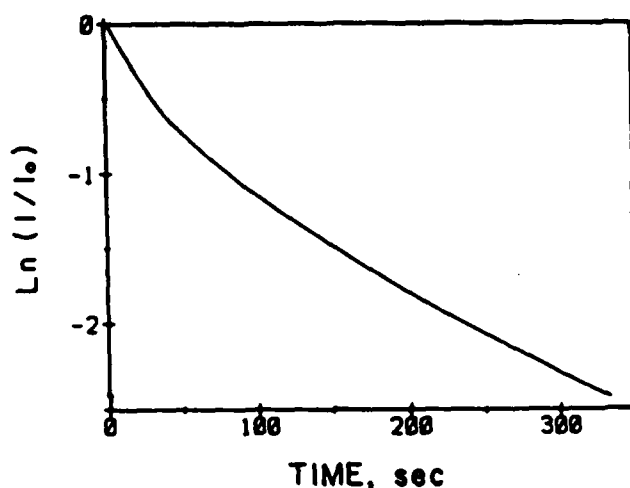

Fig. 3. Plot of ln (CL intensity) as a function of time for a ZYEBT sample having an upper-limit average loading of 0.5 TMD molecules per unit cell and ~2.6 bipyridine molecules per unit cell. Data were obtained at 64°C.

At longer times, the CL decay curves are roughly exponential, as shown in Figures 3 and 4 for several ZYEBT samples; decay can be described by a single, unimolecular rate constant k that varies with the TMD loading level. Data from the linear regime can be fit by an equation based on the Arrhenius expression, eq. (2),

$$\log k = \log A - E_a/2.3RT \tag{2}$$

where k is the first-order rate constant, A is the pre-exponential factor, E_a is the activation energy for the process, and R is the gas constant.

As shown in Figure 5 for a representative sample, plots of log k vs. T^{-1} are linear for the temperature range over which CL decay data can be acquired. The values of E_a and log A, extracted from the slopes and intercepts of the Arrhenius plots, respectively, are presented in Table 1 along with solution data, which, for benzene, are in reasonable accord with literature values.[16] Note that both E_a and log A increase with TMD loading level and in all cases are lower than their solution counterparts.

For the highest loading level, corresponding to an upper-limit average of ~7 TMD molecules per unit cell, non-Arrhenius behavior is found, as shown in Figure 6. For this system, the plot of ln (CL intensity) vs. time is initially relatively flat and then exhibits an increase in decomposition rate with time.

We also attempted to assess whether the Eu complex presumed present in the zeolite could catalytically decompose TMD. To test this possibility, the rates of TMD decomposition were determined in benzonitrile solution using $Eu(bpy)_2(NO_3)_3$ (0.17 and 0.34 mM) and 9,10-dibromo-anthracene (DBA; 0.17 mM) as energy acceptors; in the DBA experiment, EDTA was also present to sequester trace metal impurities that could catalyze the decomposition. We found that the rates were identical for the two acceptors within experimental error.
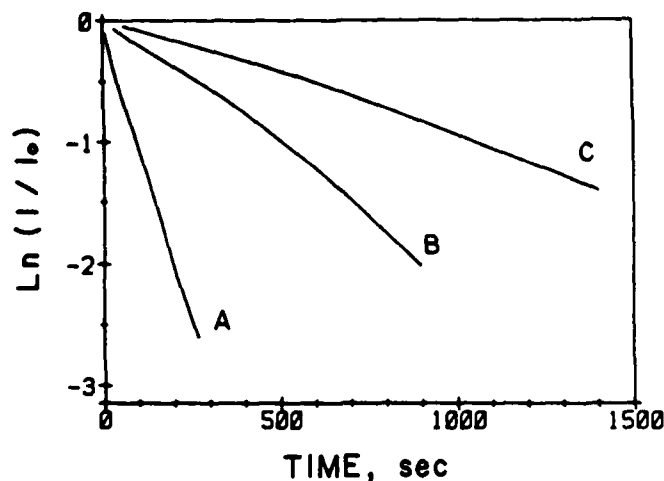
Fig. 4. Plots of ln (CL intensity) as a function of time for ZYEBT samples having upper-limit average loadings of 0.5 (curve A), 1.0 (curve B), and 2.0 (curve C) TMD molecules per unit cell; an average of ~2.8 bipyridine molecules per unit cell were present in the sample. Data were obtained at 60°C and are normalized to a common initial intensity.
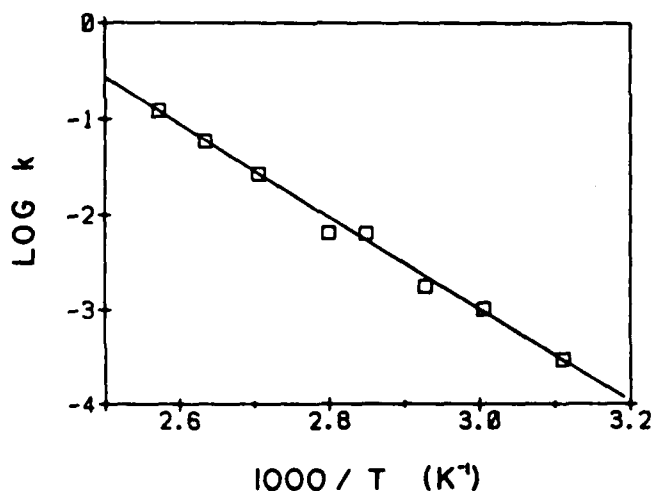

Fig. 5. Plot of log k vs. reciprocal temperature for a ZYEBT sample having an upper-limit average loading of 2.0 TMD molecules per unit cell and an average of ~2.8 bipyridine molecules per unit cell. Values of k were extracted from the exponential portion of CL decay curves like those shown in fig. 4.

We sought additional evidence for the absence of a catalyzed decomposition from relative CL efficiencies; we would expect comparable solution and ZYEBT values if the mechanism were the same. When the integrated CL decay from a benzonitrile solution containing 18 mM TMD and $Eu(bpy)_2(NO_3)_3$ (nearly saturated; ~0.2 mM) was compared to that from a ZYEBT sample with 1.0 TMD molecule per unit cell on average (representing a similar TMD concentration), the former produced more light by a factor of about 40. While these values seem quite disparate, the fact that the sorbed TMD concentration is an upper limit and that light is less efficiently collected in the zeolite experiment due to scattering could conceivably lead to similar CL efficiencies. Collectively, then, our data suggest that $Eu(bpy)_2(NO_3)_3$ does not catalyze TMD decomposition. However, other

respectively; the solutions were saturated with EDTA. Evaluation of $Eu(bpy)_2(NO_3)_3$ as a catalyst for TMD decomposition was performed in two ways. First, the decomposition rates of 0.5 mM TMD benzonitrile solutions were determined with DBA (0.17 mM; solution also saturated with EDTA) and $Eu(bpy)_2(NO_3)_3$ (0.17 and 0.34 mM) as acceptors at 74.0 and 81.6°C, using instrumentation previously described for CL measurements; the CL was monitored at 615 and 439 nm for the Eu complex and DBA, respectively. In a second experiment, solution and zeolite CL efficiencies were compared. Using a common geometry employin· a 1.0-mm pathlength cuvette, the CL decay curve of a ZYEBT sample with an average of 1.0 TMD molecule per unit cell was compared with that of a benzonitrile solution containing TMD (18 mM) and $Eu(bpy)_2(NO_3)_3$ (nearly saturated; ∿0.2 mM) as the acceptor. Integration of the intensities was done by cutting and weighing the decay plots.

   <u>Lifetime measurements</u>. Photoluminescence lifetime measurements of various Eu^{3+}-containing samples were made using instrumentation previously described.[5] Emission was excited at 337 nm and detected at 615 nm.

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